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An Innovative Procedure for the Rapid Mapping of Urban Earthquake Vulnerability

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AN INNOVATIVE PROCEDURE FOR THE RAPID MAPPING OF URBAN EARTHQUAKE VULNERABILITY

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ABSTRACT

The present paper summarizes the original approach, the different stages, the innovative algorithms and the most interesting results of a new, "simplified procedure" for mapping *Earthquake Vulnerability* in urban areas. The devised procedure is based on the processing data generated by "Remote Sensing Techniques", for the design and the construction of two different square *matrixes*: *Building Vulnerability Matrix* and *Soil Vulnerability Matrix*. Combination of *mathematical classification procedures* and *matrix analysis techniques* have been designed and implemented, for creating the *"basic models"* of the mentioned *matrixes*, together with the related *algorithms*, "ad hoc" devised. The classes and the groups generated within the described two *basic matrixes* are merged all together into a designed ***Urban Vulnerability Matrix***. Further matrix calculations are performed, generating new *"Earthquake Vulnerability Zones"*. It will then be possible, from such matrix, to construct an ***Urban Earthquake Vulnerability Zoning Map*** .

Finally, the author presents the results of the first case-history of the described new "simplified procedure": the first practical implementation has been carried out in a small town, in a high seismic area of southern Italy.

1.0.0 INTRODUCTION

«*...If you can't reduce a difficult engineering problem to just one 8.5 x 11in. sheet of paper you will probably never understand it….*»

Ralph B. PECK

1.1.0 Earthquake Vulnerability Prediction in Urban Areas: A Long Mainstream of Research

Knowledge about the *Earthquake Vulnerability Prediction* in Urban Areas is the central "core" of each correct and efficacious "Earthquake Prevention System" .
The question is an "open question", debated in many circles and discussed in several conferences and congresses.
Nevertheless *Urban Earthquake Vulnerability Prediction* is also a very interdisciplinary question that takes on considerable importance in the programming of interventions aimed above all to prevent damage deriving from the repetition of seismic events.

Long and costly detailed surveys and thoroughgoing analyses can provide rigorous solutions to the problem, which is among the most delicate and complex.
On the other hand, it is possible to define and utilize an innovative, "simplified procedure", which allows a sufficiently reliable *earthquake vulnerability* map to be drawn in a very short time.

On these mainstreams of investigation, our "Research-Institute" had developed earthquake vulnerability procedures, beginning from 1978, performing researches on the prediction of the effects that could occur, in a built-up area, after an earthquake. A new scale-model apparatus was also created and designed ad hoc, to test the behavior of pile foundations in clay, under dynamic loads [Bishop, 1981].
These Research-activities were intensified after the very strong earthquake of 23rd November 1980 [Magnitude of Main Shock: M = **6.9** on the Richter scale; Intensity at Epicenter (MSK Scale): I = **X°**; Length = about **88 seconds**], which caused great disasters in a large part of Basilicata and Campania regions in Italy [the area damaged was larger than 15,000 km^2: many structures collapsed, killing about 4.000 people; included in this number are the people who died in subsequent months, after the earthquake] [Ciuffi, 1984].
Within a period of over 25 years, the said procedures, further validated in a wide variety of research problems, have been improved progressively.

«...*Your procedure appears to be reasonable and expeditious*...» wrote Professor PECK, after reading, in 1984, the second version of the procedure [of course, it was an honor to receive his comment], which is the basis of the mentioned new "simplified procedure", discussed in the present paper, with its main stages and most important results. In particular, described in the first two parts of the paper are the informatory criteria, the *flow-chart*, the *logic architectures* and the specific methodologies of the "procedure".
The final part contains the synthesis of the first application implemented on a little town, in a seismic area, in Italy.

1.2.0 The Research Team

The present new "simplified procedure" has been created, tested and converted into specific copyrighted computer programs by a devoted Research-Team. The scholars are operating within the expansion activities of **«*intra*Vidére»** Research-Institute, which is a leading member of the so-called **«*intra*Vidére»** *Research-Chain*.
The company **«*intra*Vidére»** [Science and Art between Historical Memory and Digital Futures] is the natural evolution of creative, entrepreneurial experiences, pursued in a variety of geographical and cultural backgrounds. It provides continuity for interdisciplinary scientific and professional experiences that have evolved in different forms from as far back as **1949**.
To do research for producing innovative goods and services, "revealing" what exists in reality, but that the eye is unable to see [this is the meaning of the Latin word **«*intra*Vidére»]**, is the mission of **«*intra*Vidére»**. Its important added value is the strong synergy between **Creativity** and **Science** and the capability to ***create innovation***, designing and implementing "***Technological Integrated Processes***", in which advanced technologies and avant-garde methodologies interact for achieving specific goals, following the wave of a consolidated tradition stretching back over 50 years.

2. 0.0 INFORMATORY CRITERIA and STEPS

2.1.0 The Conceptual Approach

The vulnerability to earthquake action of a building located on a given site is essentially related to the following macro-factors [Seed *et al.*,1971].

[i])-Parameters connected with "Elevation Features":

a1)-Type, Quality and State of Conservation of the materials from which the building has been constructed;

b1)-Building's *form coefficient* {plan and elevation irregularities, severe dissymmetries, etc} and Design Criteria;

[ii]-Parameters connected with "Subsoil Features":

a2)-Geotechnical, Hydrogeologic, Geomorphologic and Geolithologic characteristics of the soils on which the Building stands;

b2)-Foundation Parameters; included in this factor are the sets of problems relative to various foundation types and therefore also all problems pertaining to soil-structure interaction;

c2)-Soil Dynamics Properties;

[iii]-Parameters connected with "Seismological Features":

a3)-Seismicity (also historical seismicity) of the Region and of the Urban Centre under study; included in this factor are the sets of questions related to the thematic area "Seismic Hazard Analyses";

b3)-Earthquake Scenarios and Seismological Parameters, Characteristics and models, related to the Urban Centre under study.

The simplified designed process (valid for the general case and therefore applicable to any built-up area) is based on the construction of an ***Urban Earthquake Vulnerability Matrix***, through different processing stages of data collected, prevalently, by *Remote Sensing Integrated Analyses*.
The elements of such a matrix are the combinations of groups of buildings and of soils, processed and classified in accordance with suitable respective parameters, generated within devoted *basic matrixes*.

2.2.0 The Steps of the Designed *Urban Earthquake Vulnerability* Process

The most important steps of the designed process, together with the *Flow-Chart* [**Fig. 1**], can be summarized as follows.

[i] A devoted "*Building Earthquake Vulnerability Matrix*" has been designed for classifying each building, in accordance with suitable parameters deriving from the crossing "Types, Quality and State of Conservation of Building Materials" and Building's *form coefficient* .

[ii] A devoted "*Soil Earthquake Vulnerability Matrix*" has been designed for zoning soils, on the basis of combinations deriving from the crossing "Geotechnical and Hydrogeological" characteristics and "Geomorphological and Geolithologic" features.

[iii] The classes and the groups generated within the described two *basic matrixes* are merged all together into a designed ***Urban Earthquake Vulnerability Matrix***. Further matrix calculations have been performed, generating new *"Earthquake Vulnerability Zones"*.

[iv] It will then be possible, from such matrix, to construct an ***Urban Earthquake Vulnerability Zoning Map*** in which the zones of the built-up area to which the study refers, having a different **relative vulnerability**, are distinguished.

It is emphasized that we are using the expression ***relative vulnerability***, because, seeing that account is not taken of the mentioned Parameters connected with "Seismological Features", the different *"Earthquake Vulnerability Zones"* only have significance within a given built-up area and cannot be compared with analogous *zones*, mapped in other urban centers.

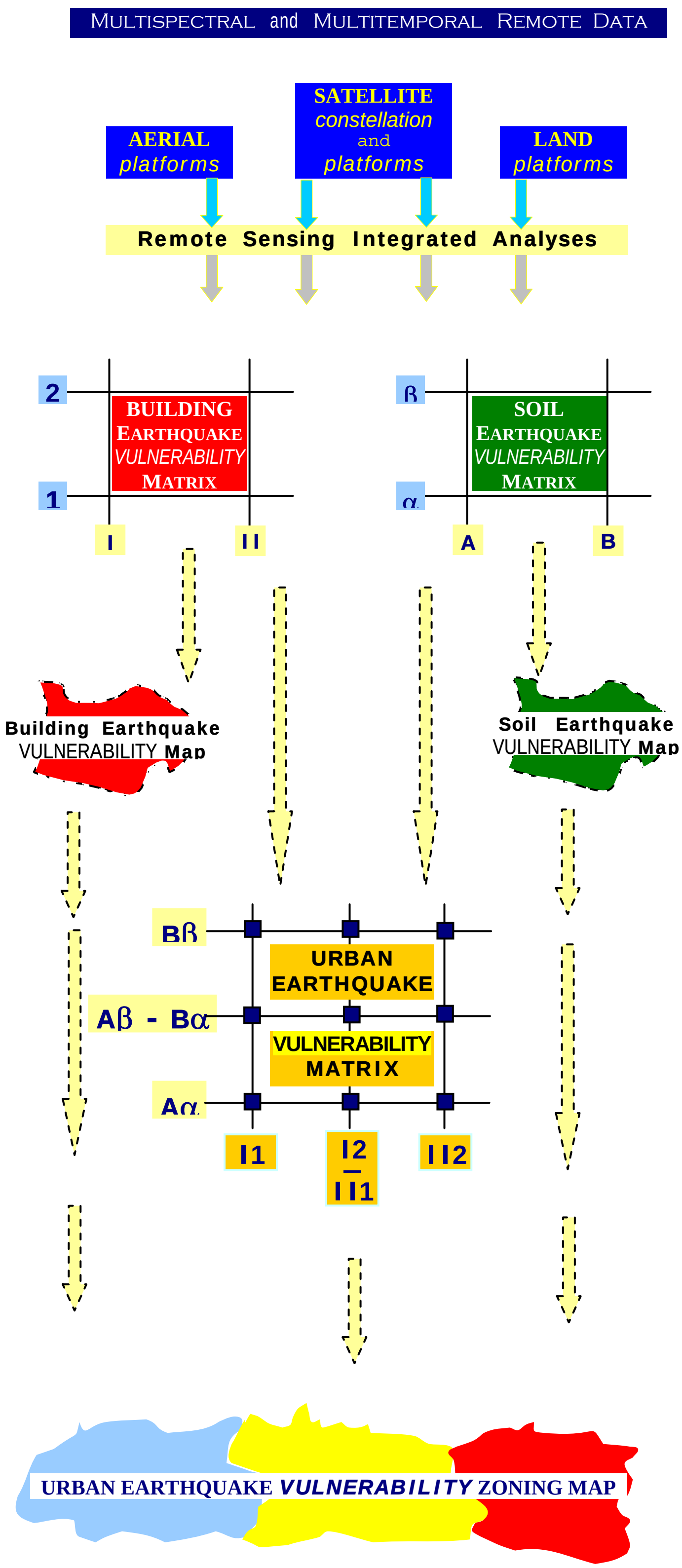


Fig. 1. *Designed Procedure's Flow-Chart*

3.0.0 REMOTE SENSING INTEGRATED ANALYSES

3.1.0 <u>*Remote Sensing Integrated Analyses*: Multispectral and Multitemporal Platforms</u>

Remote Sensing Integrated Analyses represent a crucial and basic tool for the designed <u>*Urban Earthquake Vulnerability Process*</u>.
Integrated Processing of *Multispectral and Multitemporal Images* are planned and implemented. Sophisticated analyses are carried out, collecting and processing data generated by different *Satellite* and *Aerial* platforms.
In addition, in a number of particular cases, data generated by *Land* platforms could also be collected and processed.

[i] The Satellite data are acquired by different combinations of *Sensors* and Satellite characteristics. Specific *algorithms* allow to analyze and to select, case by case, the most opportune sets of Satellite parameters, summarized, as follows:

- ▶ *Sensors* and correspondent *Spectral Bands*;
- ▶ Orbit Type, Altitude and *Spatial Resolution*;
- ▶ Repeat Cycle and Multitemporal Activities.

It is impossible, in the present paper, to discuss the different combinations of *Sensors* and Satellite characteristics adopted. For this reason, it may be appropriate to develop this sub-paragraph, adding only a short mention about the synergies and the links developed among the following combinations:

▶ **SPOT**-4 Satellite {<u>*Sensor*</u>: **HRVIR** (*High-Resolution Visible and Infrared Sensor*) – <u>*Resolution*</u>: 20 m};
▶ **IKONOS**-2 Satellite {<u>*Sensor*</u>: **OSA** (*Optical Sensor Assembly*) – <u>*Resolution*</u>: 1 m *panchromatic* (0.82 m at nadir) and 4 m *multispectral*};
▶ The large family of Satellites equipped with a *microwave high-resolution* **Synthetic Aperture Radar** (**SAR**): all weather and Day/Night acquisition capabilities; at the present time, the most important, within the said family, is **ENVISAT** Satellite;
▶ **COSMO-SkyMed** Satellite constellation, which will give a very important contribution, in the near future (full constellation will be operational by mid 2010); the constellation consists of 4 medium-size Satellites [with a large amount of <u>daily</u> acquired images], each one equipped with a *microwave high-resolution* **SAR** operating in X-band.

[ii] *Multitemporal* groups of Aerial Photographs are selected and processed.
A particular effort is performed to achieve a propaedeutic basic goal: the exact superposition among the different Multitemporal Aerial Photographs. For this purpose, each Aerial Photo selected is digitized and geo-referenced in a specific *"Basic Geographical Information System"*, after application of geometric/radiometric corrections.

The correction process removes image distortions and re-samples the imagery to a uniform ground sample distance and a specified map projection.

[iii] Data generated by *Land* platforms are acquired by a mobile laboratory and consist, prevalently, of the following distinct techniques:

- *"Multitemporal Photography in Infrared False Color"*;
- *"Multitemporal Thermographic Monitoring"* (during the day and the night);
- *"Multifrequency Radar Analyses"* .

It is interesting to note that the first two types of investigation are based on the use of what are known as "passive" *sensors*, i.e. *sensors* which record what is spontaneously "emitted" by the object.

3.2.0 *Remote Sensing Integrated Analyses*: Methods followed and Image Processing

It has already been emphasized that the constructions of the "*Building Earthquake Vulnerability Matrix"* and of the "*Soil Earthquake Vulnerability Matrix"* are, prevalently, based on "Integrated Processing of *Multispectral and Multitemporal Images"*

It has also been stressed that in a detailed study, long and "complex procedures" [in some cases, developed within the **«*intra*Vidére»** *Research-Chain*] could be implemented for providing rigorous solutions to earthquake vulnerability in an urban area.
In the case of the said "complex procedures", all the images resulting from the platforms and the techniques, briefly described above, are subjected to appropriate analog and/or digital processing.
The calculations performed are of various types, ranging from the most common to the most complex [filtering, derivation and integration, slicing, etc.] and sophisticated [calculations using "cluster analysis" *algorithms* or involving the conversion of an image into its *Fourier representation*], right up to the construction of numerical models.
The results of these calculations allow the greatest possible amount of knowledge to be "extracted" from the images in relation to specific objectives [Ciuffi *et al.*,1997].

On the other hand, in the present process, new *algorithms* have been devised to follow the same conceptual approach and the identical basic architecture of the "complex procedures", but by-passing important steps and organizing an innovative *simplified architecture* for the *rapid mapping* of the *Earthquake Vulnerability* in a built-up area.
In particular, the most original *concept-points* of the mentioned *algorithms* and of the devised *simplified architecture* can be summarized, as follows.

[i] The first *concept-point* is focused on recent new developments related to the *mathematical classification procedures*. It may be appropriate to mention here that *Cluster Analysis Methods* combined with *Matrix Analysis Techniques* have been applied following specific devoted procedures, for "soil modeling" and Geotechnical and Earthquake zoning, devised by the author since 1978-1981.
These sophisticated procedures, together with the computational *algorithms*, have been converted into specific copyrighted computer programs. As said, within a period of about 25 years, the mentioned procedures, further validated in a wide variety of research problems, have been improved progressively [Ciuffi, 2004].

[ii] The second *concept-point* regards the strong synergy between the study of the spectral characteristics of different images and a devoted image processing of the *Multitemporal Aerial Photographs*.

[iii] The third *concept-point* is related to the Innovative integration among the following techniques:

- **Image Textural Calculations** - This technique studies the spatial distribution of *radiance* values, i.e. the *electromagnetic energy* emitted or reflected by bodies, in an image of any kind;
- **Image Colorimetric Analyses -** In any image, the breakdown of the three additive primary colors (Red, Green, Blue) makes it possible to produce color analyses providing information in relation to three parameters: hue, intensity and saturation. It should be noted that the values of the hue and saturation parameters depend on the nature of the surface of the materials concerned, not on exposure.
- **Morphometrical Analyses** - Precise comparisons are made between the shapes and dimensions of different objects. Preliminary processing to ensure uniform graphic scales and make appropriate geometrical corrections precedes these analyses.

[iv] The forth *concept-point* is based on the advanced Hydrogeologic procedure, which gives an interesting contribution in achieving the following, important objectives.

- Analysis and Mapping of the "***Surface Drainage Pattern***". The study of the *"surface drainage pattern"* within an urban area – and in particular, within a historical town – requires the knowledge of several "invisible" elements buried or quite lost. For this reason, the objective has been to detect the said elements and to study them, together with the very limited visible flowing, for reconstructing the said "*surface drainage pattern*".
- Reconstruction and Mapping of the *"**Shallow Groundwater Circulation Model**"*. Data processing of a devoted *permeability matrix*, which analyzes also *fracture density* [Seed, 1981], allow the determination of the zones of ***water storage*** and the areas of ***water recharge***, together with the *preferential groundwater flow directions* and the *sheet water flow directions* [Marcolongo, 1987].

$\Sigma\Delta H$ [Total Difference]	η'' [Assigned Values]
Less than **5.00** m	**1.00**
Between **5.00** m and **10.00** m	**0.95**
Higher than **10.00** m	**0.85**

4.0.0 BUILDING EARTHQUAKE VULNERABILITY MATRIX

4.1.0 Classes Based on Types, Quality and State of Conservation of Building Materials

Building structures can be divided into the following classes:

Class **I**

- Buildings of Reinforced Concrete;
- Buildings of Good Masonry (squared blocks, solid bricks and mortar of fair quality);
- Buildings of Steel Structure;

Class **II**

- Buildings of Crumbly Masonry;
- Buildings of Masonry: the Masonry, although in a fair state, does not appear to be binding well.

It should be observed that a building whose structure is not uniformly conserved falls into one or the other class depending on whether, in the judgment of the surveyor (also by assessment of weighted average), the qualitative characteristics of one or of the other class are prevalent.

4.2.0 Classes Based on Area and Volume

4.2.1 **PaVRI** "*Plan and Volume Regularity Index*"
It is necessary, for this classification, to define a specific "*form coefficient* ", or better, a "**PaVRI**" η: "*Plan and Volume Regularity Index*". It is, for every building, the product of three terms: $\eta = \eta' \times \eta'' \times \eta'''$. The said terms are defined as follows.

η' = Ratio of the perimeter of a square of equal area to the building and the building's perimeter [**Fig. 2**];

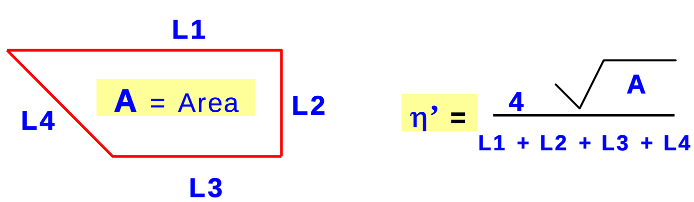


Fig. 2. Meaning of η'

η'' = Reductive coefficient due to lack of symmetry in elevation ΔH: difference in height [**Fig. 3**] between upper and lower footings, if the building should be on a slope; if the building should not be on a slope, ΔH is the difference between its maximum and minimum heights, if any; it is proposed to assign the following values to it:

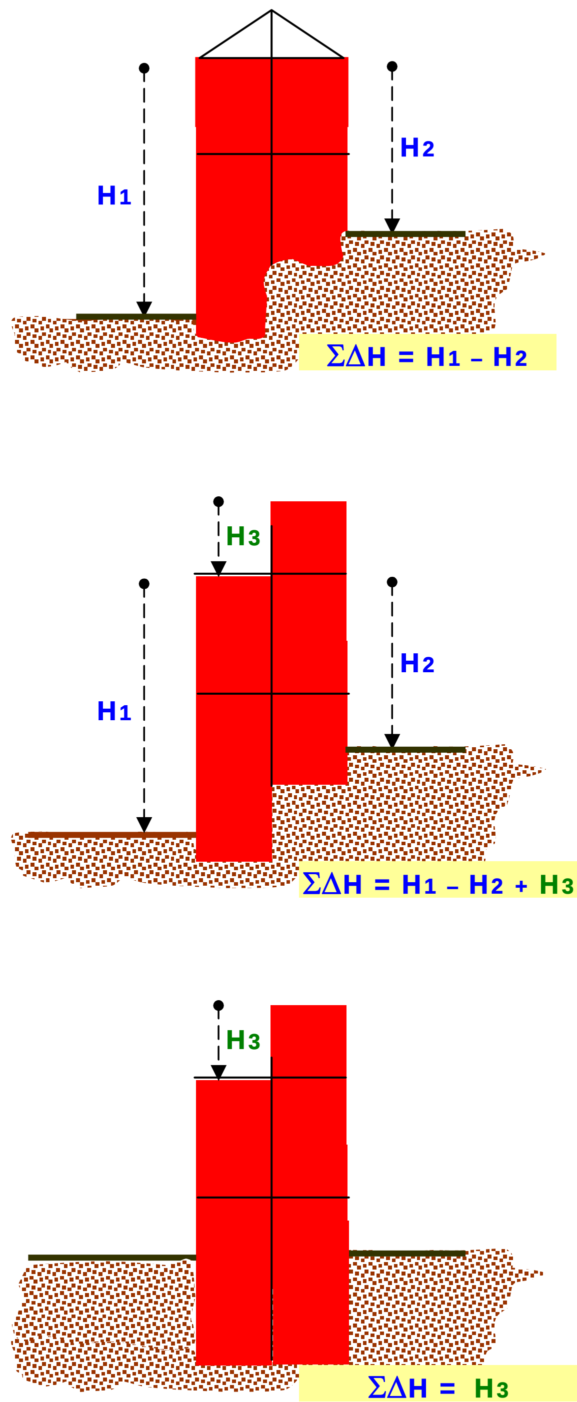


Fig. 3. Meaning of ΔH

η''' = Reductive coefficient due to the ratio between the building's maximum height [h_{max}] and η', to which the following value are assigned:

h_{max}/η'	η''' [Assigned Values]
Less than **15.00** m	**1.00**
Higher than **15.00** m	**0.95**

It may be appropriate to stress here that the values assigned to the coefficients η'' and η''' in this sub-item are not random, but rather the result of statistical analyses carried out on a number of sample zones in different built-up areas.

The division into classes on the basis of the foregoing is the following:

Class 1

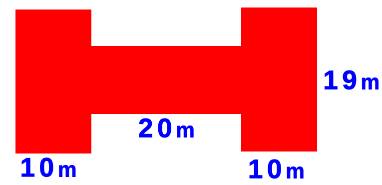
Buildings having $\eta \geq$ **0.8**;

Class 2

Buildings having $\eta <$ **0.8**

4.2.2 Considerations on the meaning of Terms η', η'', η'''

Terms η', η'' and η''' are precise engineering factors having relation to the beavior of a building in the presence of seismic activity. More specifically, they (limitedly to that which is a function of the building's plan and elevation configuration) reflect the more or less satisfactory response of the structure to dynamic loads and, in particular, to the *pseudo-static* method of analysis. This method of calculation is the most commonly adopted, especially in the case of buildings of modest dimensions and/or of limited importance.
It may be useful to recall that in a number of regulations the *pseudo-static* analysis must include "the reciprocating action of horizontal earthquake forces in two directions at right angles to each other, coincident with the main axes of the building's plan; such systems of forces, moreover, are not to be applied simultaneously".
In this scenario, particular importance is assumed by the *regularity* of the plan of the building in question. In almost all earthquake-proof designing tests it is recommended that a building's plan (at the designing stage, of course) be made as symmetric as possible in both orthogonal directions, striving to approach the square form defined as being the "ideal form" inasmuch as it achieves biaxial symmetry.
The term η', for instance, reflects the greater or lesser planimetric *regularity* of a given building in function of the greater or lesser correspondence of its plan to the "ideal" square form. It should be carefully noted that the concept, here discussed, regards planimetric *regularity* and not symmetry, since buildings exist whose plans are perfectly symmetrical but not very regular from the planimetric point of view [**Fig. 4**].



Area = 560 mq **Perimeter** = 138 m

$$\eta' = \frac{4\sqrt{560}}{138} = 0,685$$

Fig. 4. Example of a Building whose Layout is Symmetrical but Irregular

The value range of η' (significant for purposes of the present procedure) is the following:

$$0.00 < \eta' \leq 1.00$$

with η' = 1.00 in the case of a building having a perfectly square plan. However much a building's plan differs from the "ideal form" (and hence, however much it is irregular), much more η' approaches zero and, inversely, as much more as the plan of a building is similar to a square, that much more η' approaches the value of 1.00.

It is important to point out that, in a number of very special cases (it is a matter, here, of buildings whose plan is a regular polygon with $n \geq 6$ and/or buildings with a circular plan), values of η' are slightly greater than 1.00: e.g. one of the highest values is η' = 1.128, corresponding to buildings having a circular plan. In these cases, it is suggested that the values greater than 1.00 must nevertheless always be limited to η' = 1.00.

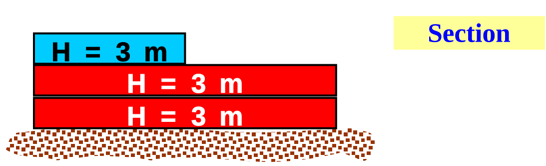
It should, finally, be noted that there is only one η' for a given building, inasmuch as it is solely a function of that building's planimetric configuration under static conditions; also for buildings with more than one storey, whose floor configurations are different for each storey, there is only one value of η' .
It is the weighted average of the values of η' corresponding to the several floors [**Fig. 5**].

The fact that more than one geometric configuration lead to the same value of η' merely means that the two configurations have the same values of planimetric *regularity*.

Then, as far as concerns the numeric values of η'' and η''' (and, more in general, all the numeric values attributed in this paper to the various coefficients), it must be reiterated that they have been assigned on the basis of statistical analyses implemented on a number of sample areas in different urban centres. It is, however, very important to stress that the main aim of this paper is to illustrate and propose a new way of approaching a complex problem such as the seismic vulnerability within an urban centre. At this stage it is not, therefore, important in the author's opinion, to discuss in detail the numeric value of the single coefficient, but rather to reflect on the conceptual approach of the proposed method.

$$\eta'1 = \eta'2 = \frac{4\sqrt{320}}{96} = 0{,}745$$

$$\eta'3 = \frac{4\sqrt{160}}{56} = 0{,}903$$



$$\eta' = \frac{[0{,}745 \times 6] + [0{,}903 \times 3]}{9} = 0{,}797$$

Fig. 5. *Calculation Example of η' in the case of Buildings with Different Plan Configurations at Various Levels*

4.3.0 Building Earthquake Vulnerability

A devoted *Building Earthquake Vulnerability Matrix* [2 x 2] has been designed for processing the interaction between the "Types, Quality and State of Conservation of Building Materials" and the "*Plan and Volume Regularity Index*" [**Fig. 6**].

Each building of the urban centre under study can be characterized, grouped and classified. In particular, every building can be assigned to one of the following Groups obtained from suitable combinations of the classes defined earlier.

[i] First Building-Group: **I$_1$**. Selected in this Group are:

▲ Buildings [reinforced concrete or good masonry buildings], having a "*Plan and Volume Regularity Index*" η ≥ **0.8**;

[ii] Second Building-Group: **I$_2$** or **II$_1$**. Selected in this Group are the following typologies:

▲ Reinforced concrete or good masonry buildings with η < **0.8;**

▲ Buildings with poor masonry, but with η ≥ **0.8**;

[iii] Third Building-Group: **II$_2$**. Selected in this Group are:

▲ Buildings of poor masonry with η < **0.8**.

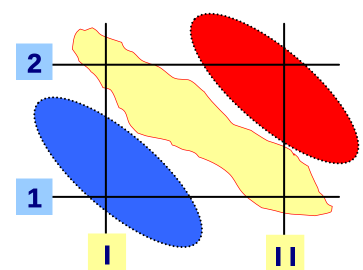


Fig. 6. *Building Earthquake Vulnerability Matrix*

The results are graphically summarized and mapped on a "***Building Earthquake Vulnerability Chart***"

This graphic document shows a first partial grouping (partial because referred solely to the buildings) of "*Seismic Vulnerability*", screened by coloring the buildings differently, depending on whether they belong to the first, second or third Group.

5.0.0 SOIL EARTHQUAKE VULNERABILITY MATRIX

5.1.0 Classes Based on Geotechnical and Hydrogeologic Characteristics

The processing stages of the interactions between Geotechnical and Hydrogeologic data allow a selection of the following classes.

Class **A**
The zones of this class are characterized by compact soils (e.g. calcareous, arenaceous), without particular problems, very suitable to support the foundations of the buildings, in static and dynamic conditions. Particular attention is given to the shallow subsoil layers. In fact, it has to be reminded that, within a historical town, the buildings [mostly, ancient masonry structures] have, in general, shallow foundations. These layers, therefore, support, in general, the footings of the superstructures and are very important for the interaction problems, also under earthquake loads [Prakash, 1981].
The index of the class most interesting features can be summarized as follows.

- ▶ Stiff Soils Outcropping, or Sub-Outcropping [depth < 4.00 m];
- ▶ Absence of *Water Storage* and *Water Recharge* Zones;
- ▶ No particular *Slope Stability* Problems;
- ▶ Absence of *liquefaction* problems;

Class **B**
This class is prevalently characterized by poor soils, not only by mechanical point of view, with a wide variety of different [often simultaneous] problems. The class most interesting features can be summarized in the following index.

- ▶ Soft Soils, Plastic Soils, Backfill;
- ▶ Surface Earth Flows;
- ▶ Soils of high *liquefaction* potential;
- ▶ Localized *Slope Stability* and/or Hydrogeological Problems.

5.2.0 Classes Based on Geomorphologic and Geolithologic Features

Selected are the following classes identified with the letters α and β. The said classes are screened on the basis of the comparative analysis of Geomorphologic and Geolithologic characteristics.
It is very important to emphasize that, for a soil, to belong to Class α, it must have all the listed characteristics; to belong to Class β, on the other hand, the presence of only one of the listed characteristics suffices.

Class α
The index of the class most interesting features can be summarized as follows.

- ▶ Slopes ≤ 35% ;
- ▶ Absence of terraces, crests, contact areas (between separate formations);
- ▶ Low Levels of *Fracture Density* {its analysis is implemented on the basis of the "*Linear Features*" (Faults and/or Fractures) detected};

Class β
Summarized in the following index are the class most interesting features.

- ▶ Slopes > 35%; also included in this class are slopes which, although ≤ 35%, prove to be unstable (e.g. active slide areas);
- ▶ Presence of terraces, crests, contact areas;
- ▶ "Weathering Covers and Landfills" or "Colluvium and Detritus" > 2.00 m

5.3.0 Soil Earthquake Vulnerability

A devoted *Soil Earthquake Vulnerability Matrix* [2 x 2] is designed for processing the interaction among the combinations of the four described classes [**Fig. 7**].

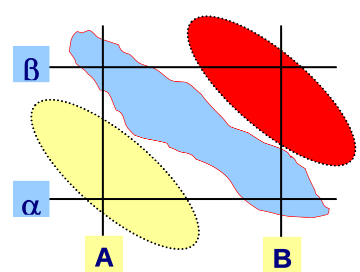


Fig. 7. *Soil Earthquake Vulnerability Matrix*

Each "homogeneous area" of the urban centre under study is characterized, grouped and classified. In particular, every "homogeneous area" can be assigned to one of the following Groups obtained from suitable combinations of the classes defined earlier.

[i] First Soil-Group: **$A\alpha$**. Selected in this Group are:

▲ Soils with good Mechanical and Hydrogeologic characteristics and a good Geomorphologic condition;

[ii] Second Soil-Group: **$A\beta$ - $B\alpha$**. Selected in this Group are the following combinations

▲ Soils having good Mechanical and Hydrogeologic characteristics but Geomorphologic problems;

▲ Soils with poor Mechanical and Hydrogeologic characteristics but a good Geomorphologic condition;

[iii] Third Soil-Group: **$B\beta$**. Selected in this Group are:

▲ Soils with poor Mechanical and Hydrogeologic characteristics and with Geomorphologic problems.

The outputs of the discussed *Soil Earthquake Vulnerability Matrix* are graphically summarized and mapped on a "***Soil Earthquake Vulnerability Chart*** "
This graphic document shows a second partial grouping (partial because referred solely to the subsoil) of *"Seismic Vulnerability"*, screened by coloring the zones differently, depending on whether they belong to the first, second or third Group.

6.0.0 URBAN EARTHQUAKE VULNERABILITY MAP

6.1.0 Urban Earthquake Vulnerability Matrix

The last step of the devised "simplified procedure" consists of preparing a final *zoning map* that expresses, the measure of the overall ***vulnerability*** level.

A devoted matrix [3 x 3] is designed and drawn for processing the interaction between the results of the *Building Earthquake Vulnerability Matrix* and the outputs of the *Soil Earthquake Vulnerability Matrix*.
The designed three-square grid matrix is named ***Urban Earthquake Vulnerability Matrix*** [**Fig. 8**].
In it, one of the three Building Groups [generated within the *Building Matrix*] corresponds to every column and one of the three Soil Groups [generated within the *Soil Matrix*] corresponds to every row.
Their possible combinations result in nine ***vulnerability-attribution*** cells.

6.2.0 Urban Earthquake Vulnerability Map

The next step is to establish the degree of danger and relative damage to assign to each of the said ***vulnerability-attribution*** cells.

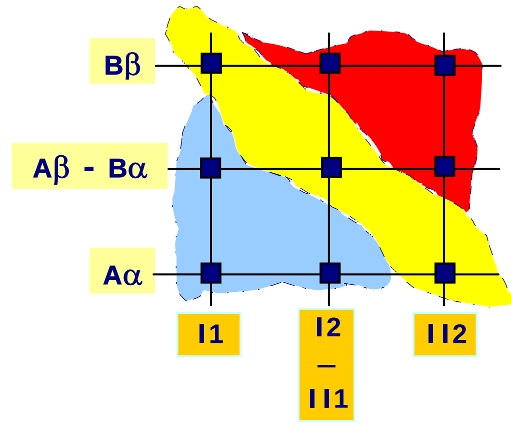


Fig. 8. *Urban Earthquake Vulnerability Matrix*

In a number of cases, it is considered to be advisable to leave this decision, which depends on the reliability of the acquired data, to the surveyor's judgment.
In fact, the greater the reliability [and the detail] of the elements collected and processed, the more numerous the aforesaid degrees can be.

Generally, the ***Urban Earthquake Vulnerability Matrix*** processing generates symmetrically three *definitive zoning classes*, **V_1, V_2, V_3**. Each class summarizes, simultaneously, interesting results and information [partially quantified] on the *vulnerability levels* of *Buildings* and *Soils* [of the urban centre under study], under earthquake loads.

These *definitive zoning classes* are the basic tools for the construction of the final document: the ***Urban Earthquake Vulnerability Map***.
The *Map*, which represents the most advanced effort of synthesis within the entire designed procedure, shows, in the case of the said three *definitive zoning classes*, the following ***vulnerability zoning*** :

[i] First ZONE: **V_1**. Mapped are the **Urban Areas** of

▶ ***LOW* EARTHQUAKE VULNERABILITY**

[ii] Second ZONE: **V_2**. Mapped are the **Urban Areas** of

▶ ***MEDIUM* EARTHQUAKE VULNERABILITY**

[iii] Third ZONE: **V_3**. Mapped are the **Urban Areas** of

▶ ***HIGH* EARTHQUAKE VULNERABILITY**

It remains to be said that, in practice, areas of little significance cannot be shown on the ***Vulnerability Map***.
By "areas of little significance" are meant very small ones contained in very large ones.
Hence, in order to be considered significant (and therefore to be shown on the *Map*) the smallest area must be at least one third as large as the largest.

7.0.0 A FIRST *CASE-HISTORY*

The devised "simplified procedure" has been applied [as a first test] experimentally to part of Calvello, in southern Italy. Calvello [730 m. above s.l.], a small town of the Basilicata Region, is to the south of Rome [nearly 350 km], in a high seismic area, which was considerably damaged by the earthquake of 23rd November 1980.

The data have been collected, analyzed, processed and classified as illustrated in the foregoing items.
It is important to to underline that [according to the basic version of the "simplified procedure"] the mentioned data are related to buildings and structures in a condition before the structure restoration projects, designed by engineers and carried out, in 8 – 10 years, after the 1980 earthquake.

7.1.0 Building Earthquake Vulnerability

The results of the *Building Earthquake Vulnerability Matrix* processing have been graphically summarized and mapped on a "***Building Earthquake Vulnerability Map***" [**Fig. 9**].

It is interesting to note a distinct prevalence of the Third Building-Group $\mathbf{II_2}$: Buildings of poor masonry with η < **0.8**.

7.2.0 Soil Earthquake Vulnerability

The results of the *Soil Earthquake Vulnerability Matrix* processing have been graphically summarized and mapped on a "***Soil Earthquake Vulnerability Map***" [**Fig. 10**].

Represented on this map is the division into zones of the area under study, on the basis of *Soil Earthquake Vulnerability* .
In this specific case, the areas marked with "**A**" are constituted by strata and banks of very rigid arenaceous soils, in blocks and stratified, with an orderly arrangement of the strata. The areas marked "**B**" consist of heterogeneous rock with a disorderly arrangement of the strata, which have a plastic behavior. The indexes "**1**" and "**2**" stand in this case for very diversified morphological situations, with steep slopes (index "**2**") in the historic centre and much less pronounced (index "**1**") in the areas west and south of the town.

It is important to underline the absence [within the *zoning map*] of the Third Soil-Group $\mathbf{B\beta}$: Soils with poor Mechanical characteristics and Geomorphologic problems.

7.3.0 Urban Earthquake Vulnerability

The ***Urban Earthquake Vulnerability Matrix*** processing generates, symmetrically, three *definitive zoning classes*, $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$.

These *definitive zoning classes* allow the construction of the final document: the ***Urban Earthquake Vulnerability Map*** [**Fig. 11**].

Distinguished on the basis of this subdivision, within the part of the town surveyed, are zones with different *degrees of Earthquake Vulnerability.* In particular, the *Map*, shows the following ***vulnerability zoning*** :

[i] First ZONE: $\mathbf{V_1}$. Mapped are the **Urban Areas** of
▶ ***LOW* EARTHQUAKE VULNERABILITY**

[ii] Second ZONE: $\mathbf{V_2}$. Mapped are the **Urban Areas** of
▶ ***MEDIUM* EARTHQUAKE VULNERABILITY**

[iii] Third ZONE: $\mathbf{V_3}$. Mapped are the **Urban Areas** of
▶ ***HIGH* EARTHQUAKE VULNERABILITY**

It becomes quite evident that the zone of greatest vulnerability is that relative to the town's ancient core, characterized by a very rugged morphology and by a very large part of ancient masonry structures, in many cases, ramshackle buildings. Included in this zone is also the medieval Castle.

Finally, it is interesting to emphasize that, in this first *case-history*, the constructed ***Urban Earthquake Vulnerability Map*** is in a very good accordance with the level and the distribution of damages, after the very strong earthquake of 23rd November 1980.

8. 0.0 CLOSING REMARKS

«...*Theory and calculations are not a substitute for judgment, but only the basis for sounder judgment*….»

Ralph B. PECK

8.1.0 Key-Expressions

The following "Key-Expressions" may be remarked.

▲ The "simplified procedure" discussed in the present paper cannot avoid the profundity of the message from professor PECK .
It's really true that each *theory* cannot be used, automatically, as a "passive tool", without any critical spirit; on the contrary, it must be viewed, case by case within its contest, with the "eye" of the "human cultural sensibility", which is unique for every person, in a specific situation.

▲ *Urban Earthquake Vulnerability Prediction* is a complex problem, but also a very interdisciplinary question that involves different thematic areas [not only in engineering and geologic fields] and requires a "global integrated approach", with devoted *logic architectures.*

▲ *Earthquake Vulnerability Prediction* in Urban Areas is the central "core" of each correct and efficacious "Earthquake Prevention System". By this point of view, the described innovative "simplified procedure" must be considered as "preventive medicine": a very useful tool for Earthquake Prevention Activities, to be applied, for its better use, *before* seismic events .
The "simplified procedure" is applicable to any built-up area and is very flexible. In fact, it could be implemented at different detail levels, corresponding to different investigation detail, timing and costs.

▲ The first practical implementation of the described *"Urban Earthquake Vulnerability Procedure"* has been carried out in a small town in a high seismic area, in Italy.
It is interesting to stress that a positive "validation" of the procedure implemented comes from the "Damage Map", showing the damages caused (in the urban area) by the very strong earthquake of 23rd November 1980.

8.2.0 Walking Towards the Future

▲ It has been emphasized, in the paper, that the devised "simplified procedure" is the new version, or better, the last, important development of a very long "Research-trip", reached gradually, over many years.
But it has been also stressed that the "Research-trip" is an "open trip". There is a need to test the "simplified procedure" in the field, in other different urban centers, for optimizing the designed new *algorithms*.

▲ A positive occasion for organizing a test program, could be the production (in progress) of the original DVD **"*JOURNEY* in ITALIAN EARTHQUAKES"**.
It has been planned, within the "Multimedia General Research-Plan", a specific role for the "simplified procedure", aimed, above all, to contribute for an important and innovative social program: the ambitious *School Earthquake-Check* program, which will also involve a large number of students.

▲ Connected with the innovations generated within the mentioned DVD, is a first report (under construction, also as "Multimedia Product"), titled "**New Discoveries and Important Lessons learned from Italian Historic Earthquakes: Interaction among *Earthquakes*, *Waters* and *Landslides***".
In this context, it is a pleasure to note that the inedited and innovative results, regarding the *Interaction among Earthquakes, Waters and Landslides* are on the same wave-length of the "hope" of professor PECK, who closed, in 2004, his amazing *Key-Note Address* [within the "Fifth International Conference on Case Histories in Geotechnical Engineering"], with this "strong" wish: «*...It is my hope that this conference and those to follow will increasingly describe interactions among geology, soil properties adequately described, construction procedures, and performance….*» [Peck, 2004].

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The author reminds, with profound gratitude, the late Eminent Professors Ralph Brazelton PECK and Harry Bolton SEED, for their early encouragement to develop further "New Research Activities" on *Urban Earthquake Vulnerability Procedures.*

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Fig. 9. {Calvello - Italy} *Building Earthquake Vulnerability Map*

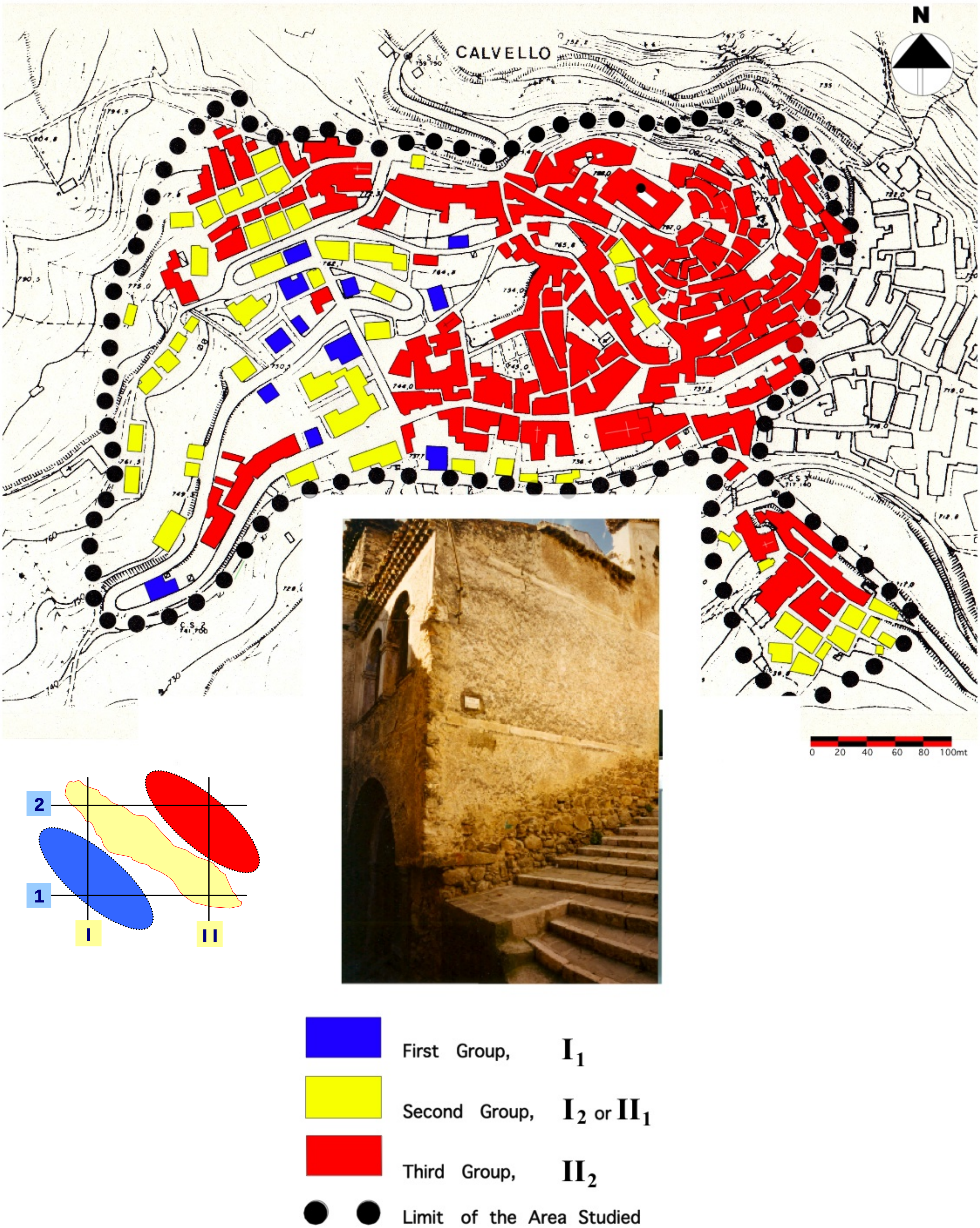
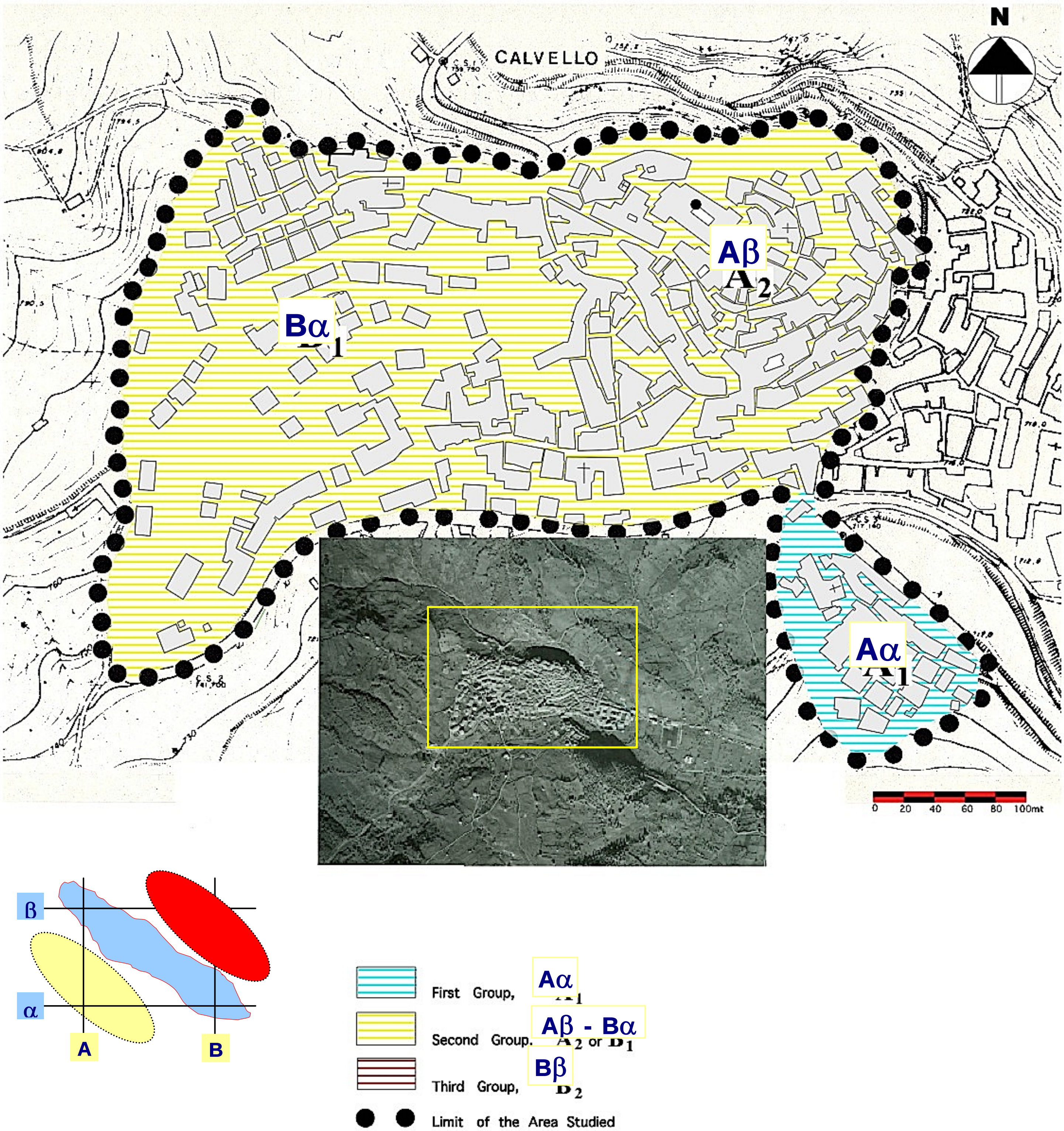


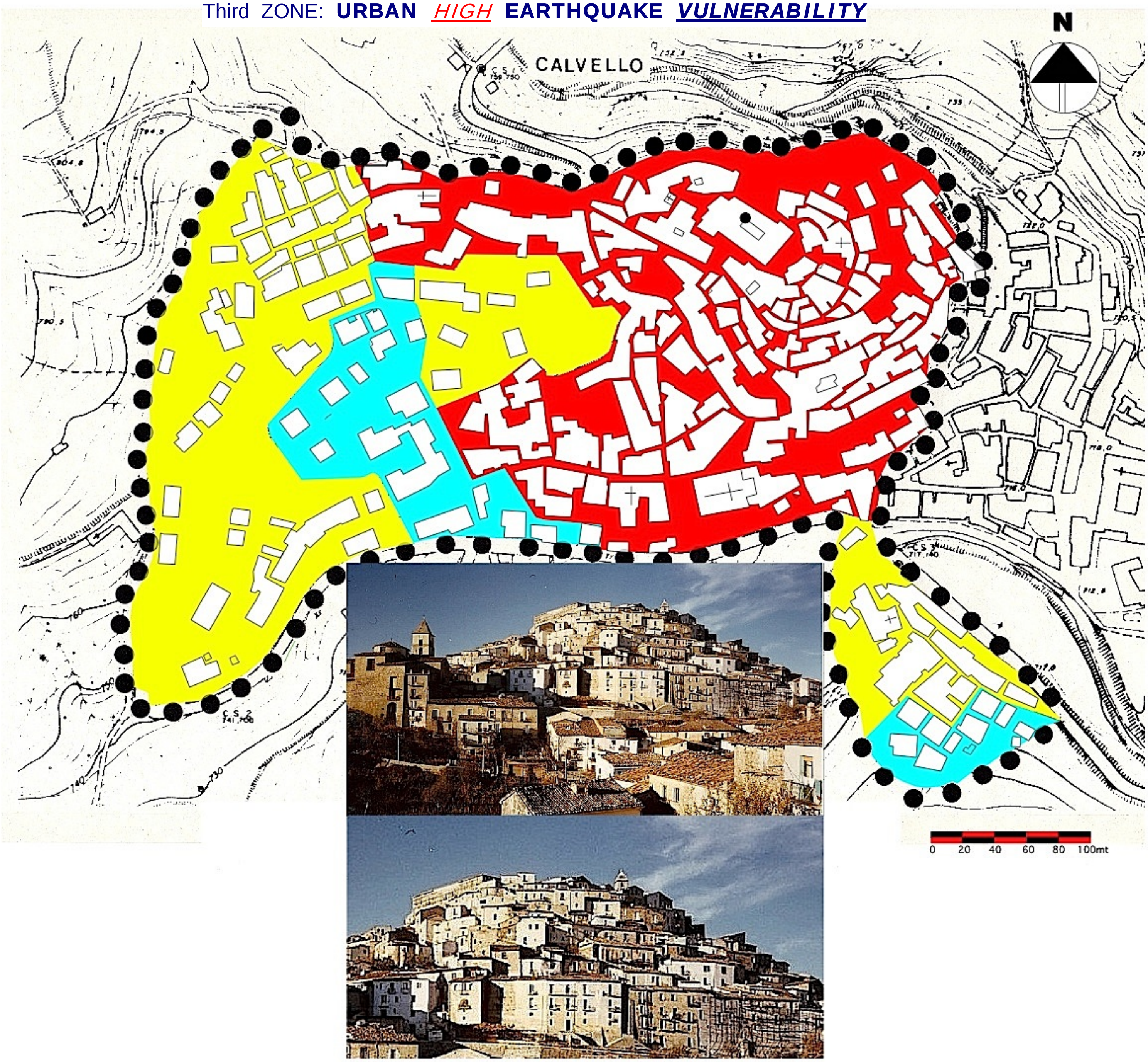
Fig. 10. {Calvello - Italy} *Soil Earthquake Vulnerability Map*



First ZONE: **URBAN** ***LOW*** **EARTHQUAKE** ***VULNERABILITY***

Second ZONE: **URBAN** ***MEDIUM*** **EARTHQUAKE** ***VULNERABILITY***

Third ZONE: **URBAN** ***HIGH*** **EARTHQUAKE** ***VULNERABILITY***



First Zone: Areas of Low VULNERABILITY

Second Zone: Areas of medium VULNERABILITY

Third Zone: Areas of Greatest VULNERABILITY

Limit of the Area Studied